Developing NDE Techniques for Large Cryogenic Tanks

Year 2 Report

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Executive Summary

The Shuttle Program requires very large cryogenic ground storage tanks in which to store liquid oxygen and hydrogen. The existing Launch Complex-39 Pad tanks, which will be passed onto future launch programs, are over 40 years old and have received minimal refurbishment and only external inspections over the years. The majority of the structure is inaccessible without a full system drain of cryogenic liquid and insulation in the annular region. It was previously thought that there was a limit to the number of temperature cycles that the tanks could handle due to possible insulation compaction before undergoing a costly and time consuming complete overhaul; therefore the tanks were not drained and performance issues with these tanks, specifically the Pad B LH2 tank, were accepted. There is a need and an opportunity, as the Shuttle program ends and work to upgrade the launch pad progresses, to develop innovative non-destructive evaluation (NDE) techniques to analyze the current tanks. Techniques are desired that can aid in determining the extent of refurbishment required to keep the tanks in service for another 20+ years. A non-destructive technique would also be a significant aid in acceptance testing of new and refurbished tanks, saving significant time and money, if corrective actions can be taken before cryogen is introduced to the systems.

Year one of this project concentrated on analysis of the current tanks located at LC-39 while cryogen was present. Year two of this project concentrated on analysis of detectible thermal variations on the outer surface of the tanks as the cryogen was drained and the inner vessel warmed to ambient conditions. Two techniques have been deployed in the field to monitor the tank. The first consisted of a displacement sensor to monitor for any expansions at the base of the tank during warm-up that could indicate a compaction issue with the insulation. The second technique was continued thermal monitoring of the tank through and after warm up. The indications noted in the thermal images were compared to bore-scope images of the annular region taken once the tank was inert and warmed to ambient conditions. Similar thermal imaging was performed on a smaller tank where an insulation void was induced to compare the effectiveness of thermal imagining on a different tank geometry.

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Background and Overview

The Shuttle Program requires very large cryogenic ground storage tanks in which to store liquid oxygen and hydrogen. The existing Launch Complex-39 Pad tanks, which will be passed onto future launch programs, are over 40 years old and have received minimal refurbishment and only external inspections over the years. The majority of the structure is inaccessible without a full system drain of cryogenic liquid and insulation in the annular region. It was previously thought that there was a limit to the number of temperature cycles that the tanks could handle due to possible insulation compaction before undergoing a costly and time consuming complete overhaul; therefore the tanks were not drained and performance issues with these tanks, specifically the Pad B LH2 tank, were accepted. There is a need and an opportunity, as the Shuttle program ends and work to upgrade the launch pad progresses, to develop innovative non-destructive evaluation (NDE) techniques to analyze the current tanks. Techniques are desired that can aid in determining the extent of refurbishment required to keep the tanks in service for another 20+ years. A non-destructive technique would also be a significant aid in acceptance testing of new and refurbished tanks, saving significant time and money, if corrective actions can be taken before cryogen is introduced to the systems.

Year one of the project demonstrated the usefulness of thermal imaging as a health monitoring tool for in-use tanks. The second year of this project has expanded on the idea of thermal imaging of a cold tank by monitoring the Pad B LH2 tank during and after drain of the LH2 and subsequent warm-up of the inner vessel required for refurbishment efforts. The intent of this monitoring was to determine the feasibility of using thermal imaging as a tool to detect insulation voids in unfilled cryogenic tanks. Also deployed in the field during the warm-up phase was a displacement sensor to monitor for any anomalous displacement of the base of the tank that could be an indicator of significant perlite compaction.

To compliment the field imaging, a mathematical analysis was performed on a simplified tank model to demonstrate the feasibility of a detectable temperature difference between a void and the surrounding area. This analysis compared a tank geometry similar to the Pad B LH2 tank as well as a smaller tank geometry. These two tank geometries were used to validate experimental imaging performed in the field at the launch pad and using a smaller double-walled spherical tank in which an insulation void was created.

LC-39 LH2 Pad B Tank

LC-39 cryogenic hydrogen storage tanks are 70 feet diameter double walled spherical tanks with granular perlite insulation in the annular region between the tanks. Thermal imaging has been used in the past to investigate an anomalous region on the west side of the Pad B LH2 tank. This region is visually detectable due to mold growth on the tank surface as seen in Figure 1. This area is much colder than the surrounding tank surface and has been proven to be due to a perlite insulation void below the surface in the annular region between the inner and outer shells. The additional heat flow through this region of the tank caused a significantly higher hydrogen loss rate on the Pad B tank as compared to the Pad A tank. With the poor performance history and the need to perform facility repairs and modifications, the Pad B LH2 tank was approved for refurbishment efforts begun in 2009. The anomaly on the west side of the tank and the availability inspect the annular region of the tank as refurbishment began made the Pad B LH2 tank the perfect vessel for demonstration of NDE techniques.

Figure 1: LC-39 Pad B tank; "cold spot" near the top of the tank by the vent line

Displacement Sensor

In November of 2009 it was decided to drain the liquid hydrogen in the Pad B LH2 tank in order to facilitate facility modifications, repairs, and inspections of the insulation and annular region. The drain of the cryogen from the tank allowed for monitoring instrumentation to be employed during the process. The intent of the monitoring instrumentation was to listen for indications that may provide information on the state of health of the tank as it was warmed. This information could then be used to determine the extent of the refurbishment required to bring the tank to a state where it could support future launch programs with high reliability. Instrumentation included strain gauges, vacuum gauges and a displacement sensor.

Work under this project allowed for the packaging and monitoring of the displacement sensor supporting the tank drain and warm-up operation. It was theorized that if extensive perlite compaction had taken place at the base of the LH2 tank, when the inner tank expanded as it warmed from cryogenic to ambient temperatures, the weight of the inner vessel would be transferred to the outer vessel causing a measureable displacement in the outer vessel. Under non-compacted insulation conditions, the insulation would simply flow around the inner vessel as it expands and the inner vessel would continue to be supported by the 40 tie rods located near the equator.

A commercially available laser displacement sensor was packaged into a positively pressurized housing to allow for placement in a Class I Div II hazardous location and shown in Figure 2. The sensor was placed at the lower most point of the tank. A "ring" was attached to the tank where the displacement sensor was located to keep rain and dew from dropping on the window at the top of the housing and causing false readings.

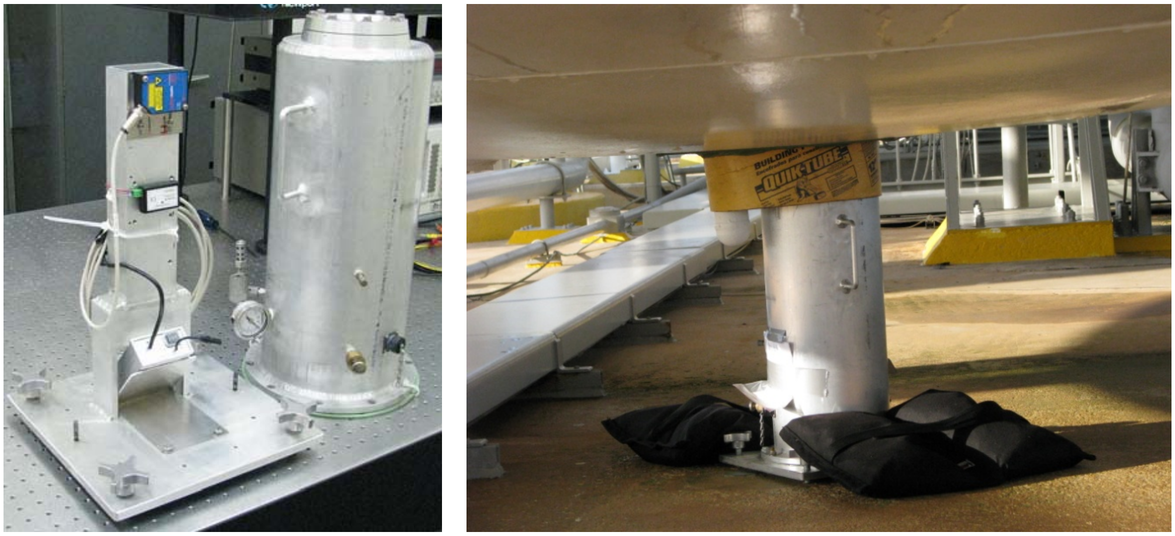

Figure 2: Displacement Sensor housing and placement under the Pad B LH2 tank.

Data was retrieved from the system each week for a two month period immediately following the burn-off of the remaining hydrogen in the tank. During this time the inner vessel warmed from -423°F to approximately 17°F. The data correlated well with the daily thermal variations as can be seen in from the data in Figure 3. A few anomalies in the data were theorized to be due to insect activity over the widow at the top of the housing. Overall, no major indications were noted from the displacement sensor data, strain gauge data, or vacuum readings which would indicate that anything anomalous was going on in the tank and which would require more extensive inspections or a refurbishment requiring a full insulation drain.

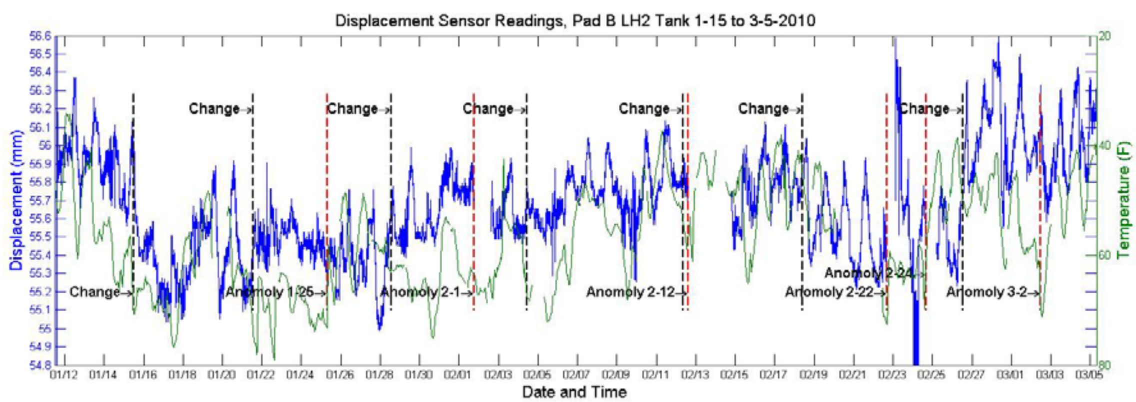

Figure 3: Displacement sensor data graphed along with ambient temperature data.

Heat Transfer Model

Thermography has successfully been used to monitor the tanks for areas of increased heat transfer when they were filled with cryogenic liquid. Because of the large thermal mass of the inner and outer spheres of the tanks, heat transfer between surfaces to equalize temperatures can be relatively slow, therefore, thermography has been suggested as an aid in acceptance testing of the tanks before cryogen is introduced to any tank, new or refurbished. Simplified models using ideal environmental

conditions show that temperature difference of a few degrees Fahrenheit could be achieved and would be easily detected by current long-wave and mid-wave infrared cameras.

The assumptions used in our simplified model are that the heat coming in from a source onto a tank is equal to the heat absorbed by the outer shell, resulting in an increased temperature, plus the heat transferred back out to the environment through radiation and convection and the heat transferred to the inner sphere by radiation and conduction/convection. The model assumes infinite parallel plate geometry with a stationary and constant heat source. These assumptions greatly simplify the actual configuration, but as the true situation is difficult to model (the effects of sun/tank angle, cloud cover, convective losses due to wind), it is a starting point that can be compared to experimental results.

For no insulation in the annular region we have:

$$\left(\frac{Q}{A}\right)_{source} dt = \rho \delta c_{p_{steel}} dT + \left[\epsilon_p \sigma \left(T_T^4 - T_B^4\right) + h_b (T_T - T_B) + \epsilon_e \sigma \left(T_T^4 - T_I^4\right) + h_t (T_T - T_I)\right] dt$$

For insulation in the annular region we have:

$$\left(\frac{Q}{A}\right)_{source} dt = \rho \delta c_{p_{steel}} dT + \left[\epsilon_p \sigma \left(T_T^4 - T_B^4\right) + h_b (T_T - T_B) + k \frac{(T_T - T_I)}{l}\right] dt$$

The two equations can be rearranged as follows:

$$dT = \frac{1}{\rho \delta c_p} \left\{\left[\left(\frac{Q}{A}\right)_{source} + \epsilon_p \sigma T_B^4 + \epsilon_e \sigma T_I^4 + h_b T_B + h_t T_I\right] - \left[(\epsilon_p + \epsilon_e)\sigma\right] T_T^4 - [h_b + h_t] T_T\right\} dt$$

$$dT = \frac{1}{\rho \delta c_p} \left\{\left[\left(\frac{Q}{A}\right)_{source} + \epsilon_p \sigma T_B^4 + \frac{k_g T_I}{l} + h_b T_B\right] - [\epsilon_p \sigma] T_T^4 - \left[\frac{k}{l} + h_b\right] T_T\right\} dt$$

Where,

t = time
T=temperature
ϵ_e=effective emissivity between tank surfaces
σ=Stefan-Boltzmann Constant
Other variables are defined in Table 1.

The above equations were plotted for various scenarios using the assumptions given in Table 1 for two different tank geometries. These geometries were chosen to resemble the two tanks that were accessible for imaging.

Table 1: Values used for comparison of external surface temperatures of empty double-walled cryogenic storage tanks.

	Large Tank with Insulation	Large Tank without Insulation	Small Tank with Insulation	Small Tank without Insulation
Input heat, $\left(\frac{Q}{A}\right)_{source}$ (surface is at an angle to the sun)	500 W/m^2	500 W/m^2	500 W/m^2	500 W/m^2
Emissivity of outer surface of outer tank wall (white paint), ϵ_p	0.9	0.9	0.95	0.95
Emissivity of inner surface of outer tank wall $\epsilon_{io_{inner}}$	0.8 (oxidized)	0.8 (oxidized)	0.1 (polished)	0.1 (polished)
Emissivity of outer surface of inner tank wall, $\epsilon_{i_{outer}}$	NA	0.1	NA	0.1 (polished steel)
Effective emissivity between tank walls, $\epsilon_e = \frac{\epsilon_{i_{outer}}\epsilon_{i_{inner}}}{\epsilon_{i_{outer}}+\epsilon_{i_{inner}}-\epsilon_{i_{outer}}\epsilon_{i_{inner}}}$	NA	0.1	NA	.05
Thickness of outer tank wall, δ	11/16 inch	11/16 inch	0.087 inches	0.087 inches
Density of outer tank wall, ρ	8000 kg/m^3	8000 kg/m^3	8000 kg/m^3	8000 kg/m^3
Heat capacity of outer tank wall, $c_{p_{steeel}}$	500 J/kg-K	500 J/kg-K	500 J/kg-K	500 J/kg-K
Insulation Effective Conductivity in annular region, k	0.04 W/m-K	NA	0.04 W/m-K	NA
Approximate value for coefficient of heat transfer for natural convection of air from the tank to the environment (light wind), h_b	10	10	10	10
Approximate value for coefficient of heat transfer for natural convection of air in the annular region h_t	NA	2	NA	2
Width of annular region, l	50 inches	50 inches	5.42 inches	5.42 inches
Background Temperature, T_B	290 K	290 K	290 K	290 K
Outer tank wall temperature (initial), T_T	300 K	300 K	300 K	300 K
Inner tank wall temperature (assumed to be a heat sink, constant), T_I	300 K	300 K	300 K	300 K

The results of the calculations demonstrate that the large tank geometry can maintain a larger temperature difference between areas with and without insulation than the smaller tank because overall less heat is lost to the inner tank surface; however it takes longer for this temperature difference to develop because of the more massive outer shell. Further analysis is required to determine the minimum size of a detectable void.

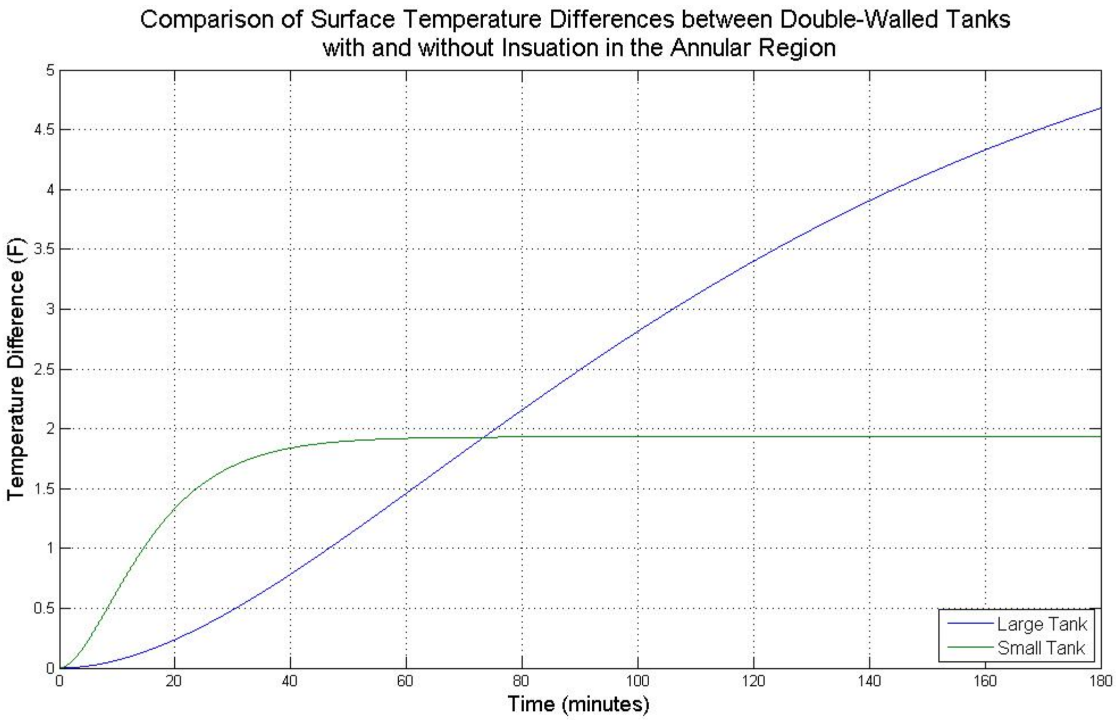

Figure 4: Variations in surface temperature between tanks with and without insulation in the annular region of two different parallel-plate tank configurations.

Thermal Imaging of Pad B LH2 Tank

The anomalous region on the west side of the Pad B LH2 tank was imaged throughout the warm-up phase of the tank drain operation. The void size and shape determined from the bore-scope inspections corresponds well with pervious thermal images taken of the area. Figure 5 shows one of the images obtained from bore-scope inspections giving an indication of the size of the void space. Figure 6 shows a thermal image of the tank from March 8, 2010 showing the outline of the “cold spot” on the tank. The bore-scope inspections revealed that much of the area had some percentage of insulation over the inner vessel, however the area below the mold growth on the outer tank shell had only a light dusting of insulation so that the inner tank was effective exposed in this area.

Figure 5: Annular region void space

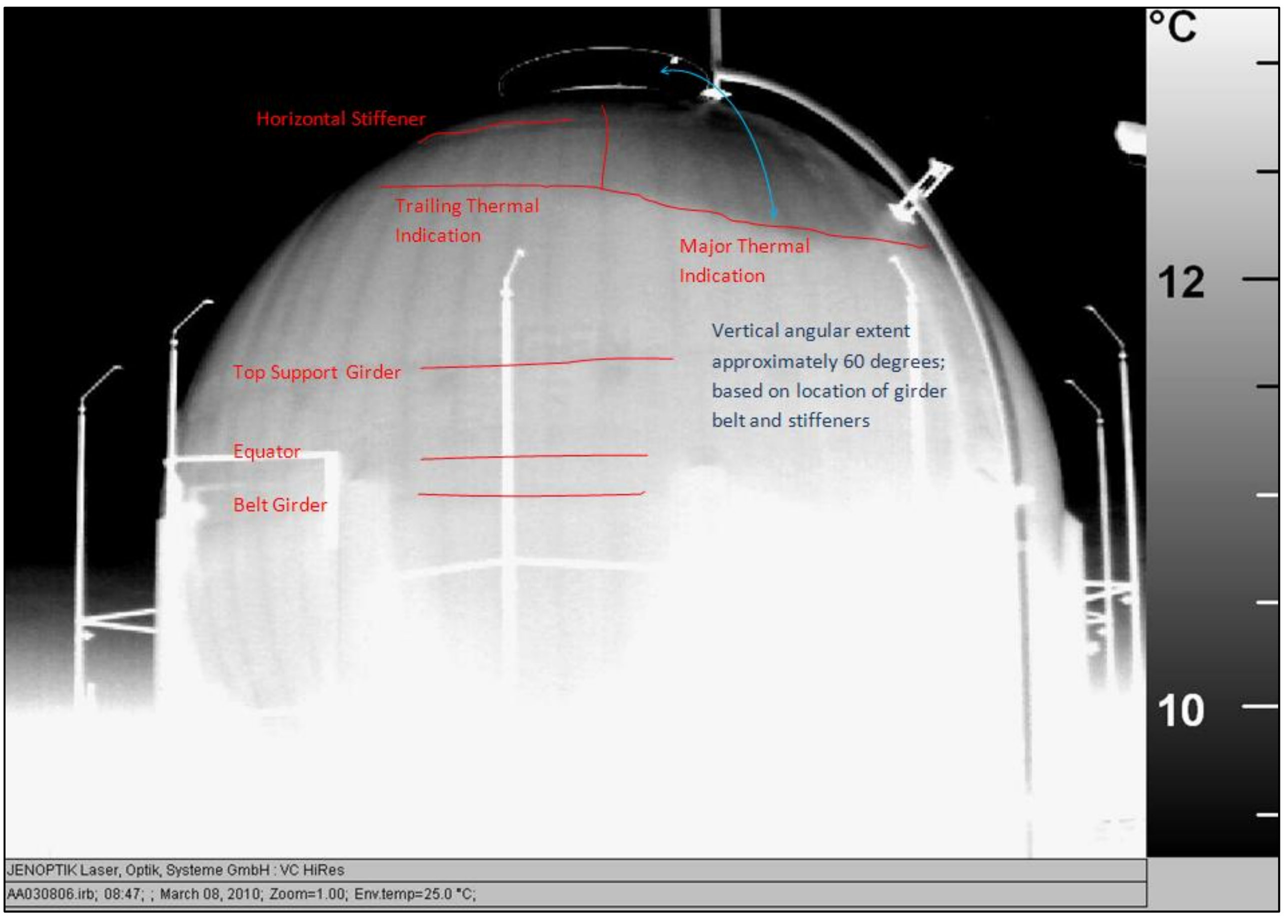

Figure 6: Size and location of void space estimated from thermal image obtained in March after liquid hydrogen had been removed from tank but prior to complete warm-up of the tank.

Thermal images were obtained throughout the drain of the liquid hydrogen from the Pad B tank and during the warm-up period. The following sequence of images shows the void region when the tank

contained liquid hydrogen, when it was drained of liquid hydrogen but below ambient temperatures, and after the system was warmed to ambient conditions (following bore-scope inspections). The sequence of images indicates that the void region is still detectable even when the cryogen is not present. As the model predicts for a tank with an outer shell of carbon steel and a corrosion layer on the inner side of the vessel (resulting in an increased thermal emissivity) with a stainless steel inner vessel, a few degrees temperature difference was detectable. This field data differs from the model due to many factors including the differences in spherical vs. flat plate geometry, variations in sun angle, cloud cover, and wind speed. Though differences exist, the combination of theoretical and observed temperature differences give evidence that thermography may be a viable technique for void detection depending on tank geometry and the environmental conditions under which images are obtained.

Figure 7. The image was taken on January 26, 2009 at 2:15 PM with a Jenoptik VarioCam LWIR camera. Liquid hydrogen remained in the tank and the annular region pressure was < 1e-5 Torr.

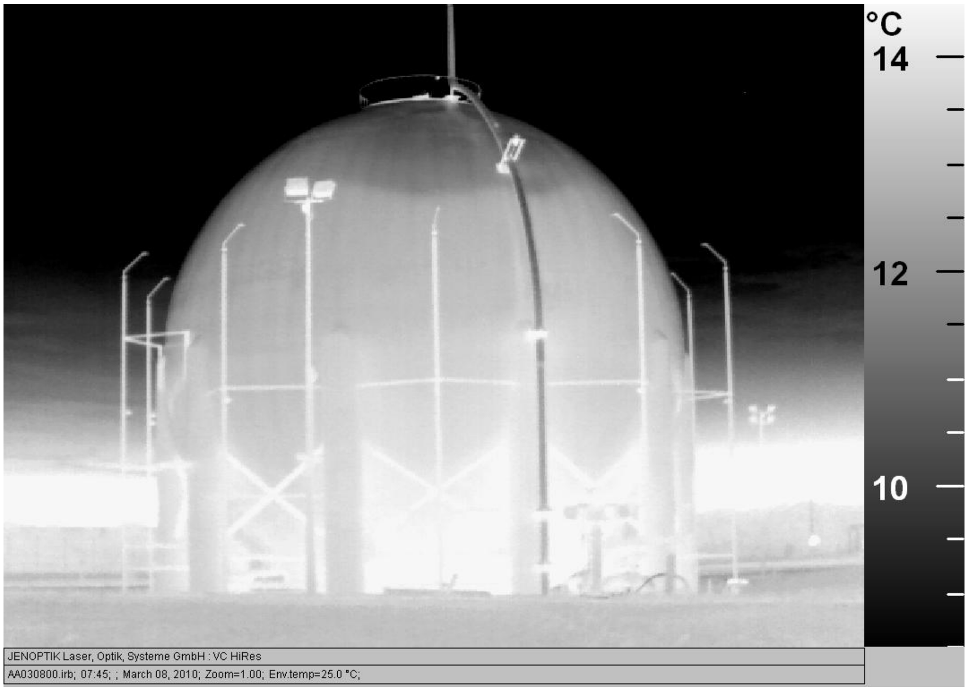

Figure 8. The image was taken on March 9, 2010 with a Jenoptik VarioCam LWIR camera. The inner tank temperature was approximately 6°F and annulus pressure was 3.5 PSIA. Overcast skies provided for good imaging as the moldy area did not absorb heat as readily as with direct sunlight and therefore did not mask the visibility of the cold spot.

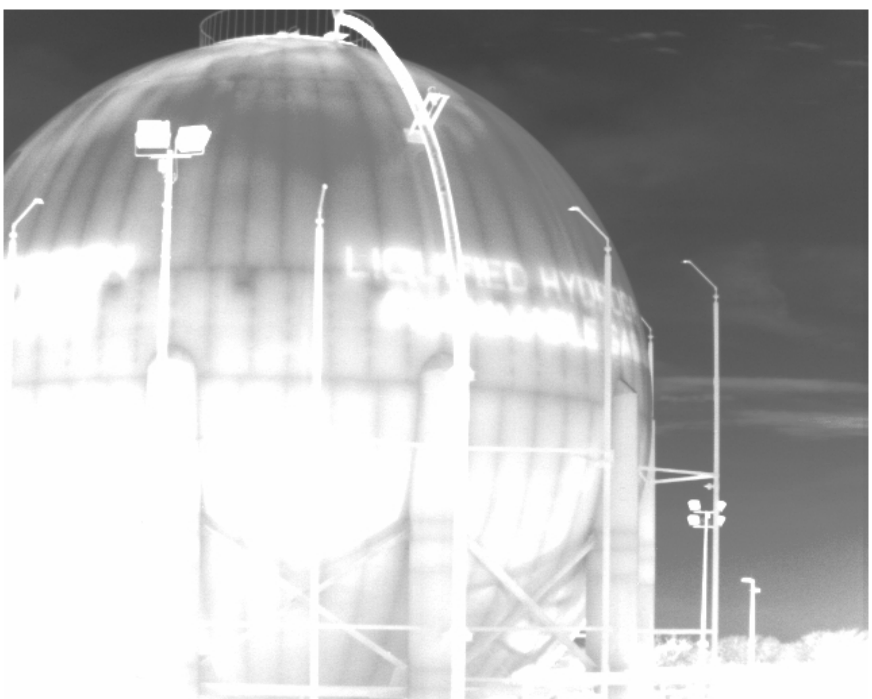

Figure 9. This image was taken on 6/29/2010 at 11:40 AM with a Titanium 560 MWIR camera. The inner vessel temperature is near ambient temperatures and the annular region pressure is at one atmosphere.

Stainless Steel Tank Imaging

A smaller five-foot diameter liquid nitrogen tank of spherical design with stainless steel inner and outer shells, shown in Figure 10, was used to perform a similar imaging sequence as that performed on the Pad B tank. We had the ability with the small tank to create an artificial void to image by only filling the annular region half way with insulation.

During imaging, attempts were made to keep the environmental conditions as consistent as possible between image sets. Most importantly we attempted to image only on days with mostly clear skies so as not to confuse the images with cloud reflections on the tank surface. The tank temperatures were measured via thermocouples attached along a rod connected to the outer shell as shown in the schematic shown in Figure 11. This location corresponds to the dark point near the feedthrough on the right side of the tank seen in Figure 12.

Figure 10: Imaging location for 5-foot diameter double walled cryogenic storage tank.

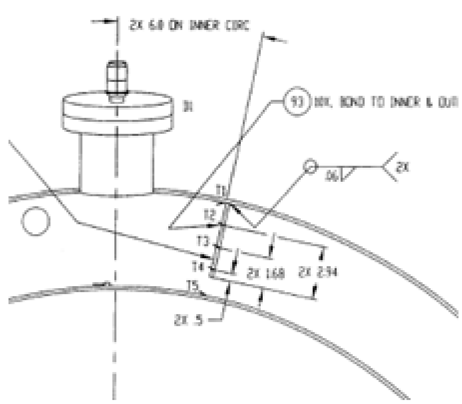

Figure 11: Location of thermocouple rod in the annular region of the 5-foot diameter tank.

The first set of images, taken on 9/14/2010, shows the tank with insulation filing the entire annular region and filled with a limited quantity of liquid nitrogen to chill the inner vessel. The temperature

difference between the thermocouple on the inner shell and that on the outer shell was 170°F. The only cold spot on the tank is in the area where rod holding the thermocouples is attached to the outer shell. Differences in apparent temperature near the equator are sharp and caused by reflections from surrounding buildings. On average temperature differences between the top and bottom hemispheres is minimal, perhaps one or two degrees after approximately two hours of chilling the inner vessel with liquid nitrogen.

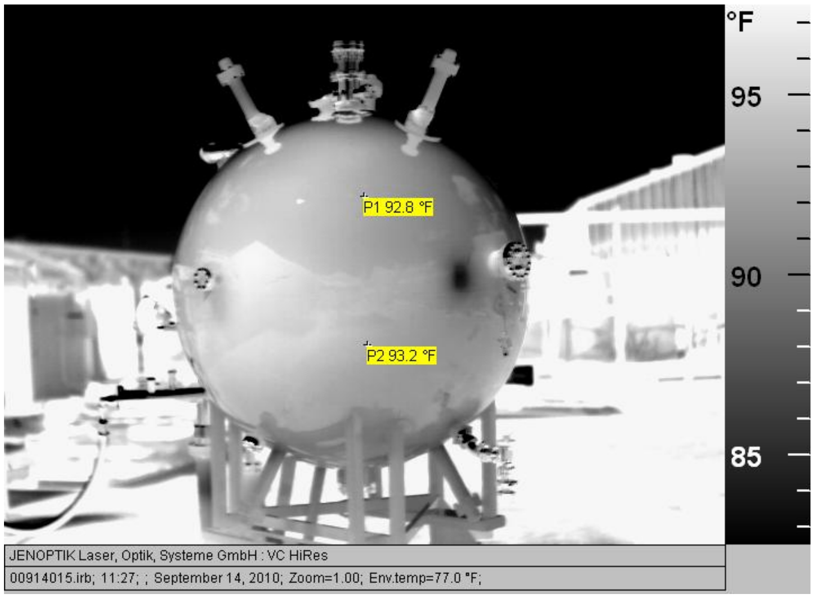

Figure 12: Image on 9/14/2010 at 11:27 am with full insulation in the annular region and after approximately two hours of chilling with liquid nitrogen.

We can compare this image taken with full insulation to images taken on 8/17/2010 and 8/18/2010 where liquid nitrogen was introduced to chill the inner shell and where the annular region was only half filled with insulation. The temperature difference between the inner and outer vessels at the time of the image in Figure 13 was approximately 100°F. There is an easily discernable temperature difference between the top and bottom hemispheres of the tank. This data was used to validate that the insulation filled approximately half of the annular volume. The apparent temperature difference between the top and bottom hemispheres is in the range of 15°F.

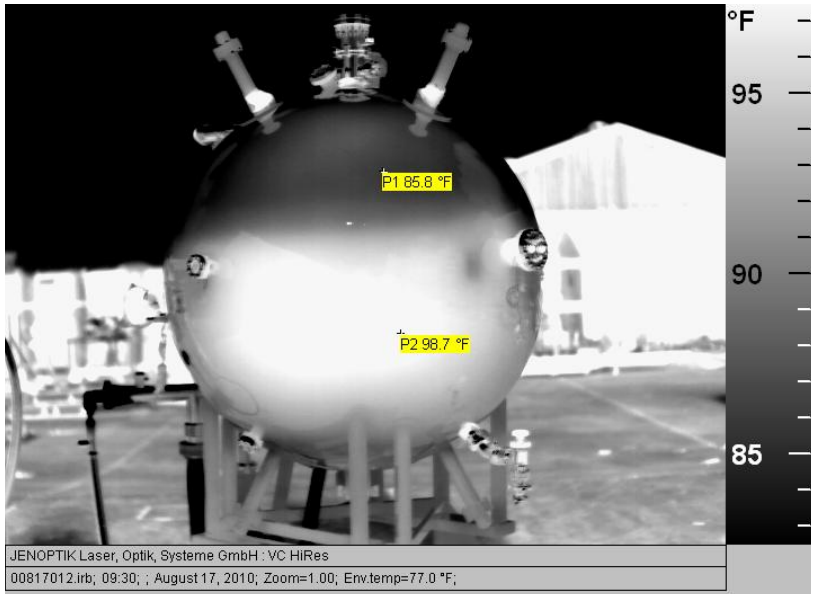

Figure 13: Image taken on 8/17/2010 at 9:30 am with an annular region only ½ filled with insulation and after chilling the inner vessel with liquid nitrogen.

The next step in the imaging sequence was to reduce the temperature difference between the inner and outer vessels. Data on 8/18/2010 provided approximately a 50°F temperature difference between the inner and outer vessels over a 2 ½ hour period, resulting in an outer shell upper and lower hemisphere temperature difference of approximately 8 to 10°F.

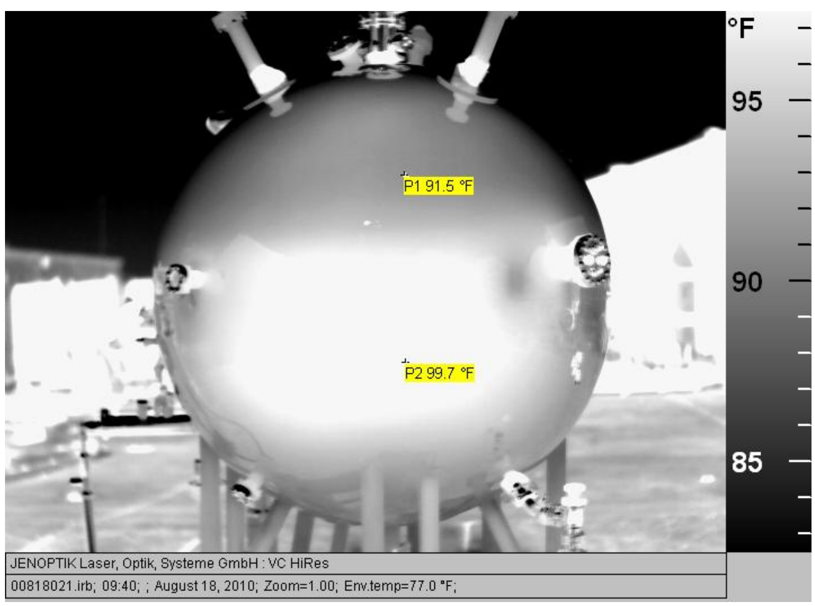

Figure 14: Image taken on 8/18/2010 at 9:40 am with an annular region only ½ filled with insulation and after chilling the inner vessel with liquid nitrogen.

The final step in the process was to image the tank without introducing liquid nitrogen into the system so that the temperature difference between the inner and outer sphere was naturally occurring due to daily temperature variations. In this case, a slight temperature variation between the

hemispheres was noted, however in comparing this temperature difference to that from a 9:07 am image taken on 9/14/2010 with full insulation and prior to filling the tank with LN2, the difference is not significant. The slight temperature variation in the two images is likely due to reflections from the sky and ground and so cannot be used to definitively say that an insulation void exists.

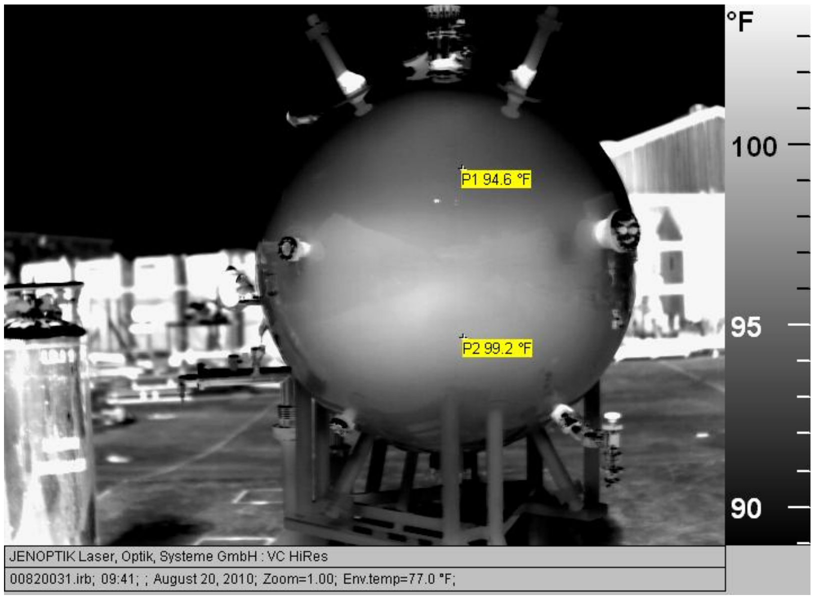

Figure 15: Image taken on 8/20/2010 at 9:40 am with an annular region only ½ filled with insulation and no chilling of the inner vessel with liquid nitrogen.

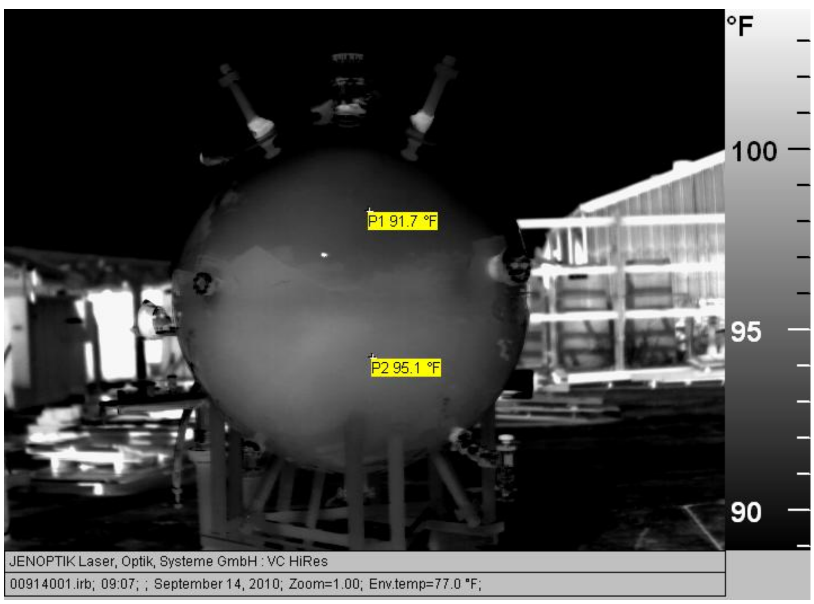

Figure 16: Image taken on 9/14/2010 at 9:07 am with an annular region completely filled with insulation and prior to chilling of the inner vessel with liquid nitrogen. Image is dark so that the same temperature scale can be used for comparison to Figure 15.

The results of the thermal imaging of the 1000 liter tank indicate that for this geometry and outer sphere material, indications of insulation voids are not likely without some induced temperature

difference on the inner sphere. This agrees fairly well with the mathematical model indicating that the temperature difference between areas with and without insulation would be limited for this type of geometry.

Summary

In summary, thermal imaging may be a very valuable tool for assessing the insulation state of large cryogenic tanks prior to filling with cryogen, however the usefulness of thermal imaging of small tanks is limited because of the small annular width and increased heat flow to the inner vessel. The biggest payoff for early detection of voids prior to putting tanks into cryogenic service is with the large tanks, especially those designed for annular regions held under vacuum, where draining the system is costly and time consuming. In these large tank geometries, thermography has proven a relatively successful tool and imaging and analysis would be beneficial and cost effective when bringing any new or refurbished tanks into service.

Future work

Thermography may be a useful tool for insulation void detection, but insulation compaction is also a concern for tank health as it could cause mechanical failure. In this case thermography would be of no use because the variation in thermal conductivity between normal and compacted insulation is minimal. Should bore-scope inspections and perlite sampling through available ports have not been successful and deemed sufficient for a high confidence that the existing insulation in the Pad B LH2 tank was in good health, additional sampling ports would have been required to have been cut into the outer shell of the vessel to allow for inspection. This would have been an action of last resort as no additional leak points or areas of weakness are desired in a pressure vessel. As decisions approach for refurbishment of the other LC-39 cryogenic storage tanks, it is desirable to have a non-invasive NDE method to determine the state of compaction of insulation in the annular region. The use of a spectroscopic technique, prompt gamma neutron activation, has been proposed as just such a method and will be investigated in the third year of this project. A test box simulating a section of the LH2 vessels is under construction and will be tested in collaboration with and at Goddard Space Flight Center.

Also to be accomplished in FY 2011 is a perlite top-off of the Pad B LH2 tank. Work is planned to monitor the top-off process and inspect the tank following the insulation fill using thermal cameras. A comparison of the post insulation top-off thermal images should confirm the ability to use thermal imaging for insulation void detection in these large cryogenic vessels.